11.11 INFLUENCE OF SEA SURFACE TEMPERATURE, TROPOSPHERIC HUMIDITY AND LAPSE RATE ON THE ANNUAL CYCLE OF THE CLEAR-SKY GREENHOUSE EFFECT

Hua Hu and W. Timothy Liu

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

1. INTRODUCTION

The clear-sky greenhouse effect depends on the atmospheric absorptivity, temperature at the surface and in the atmosphere (Raval and Ramanathan, 1989). In clear sky, water vapor is the major absorber. Interactions between the clear-sky greenhouse effect and its influencing factors are very complicated, and the sensitivity study can not be obtained by using the spacebased observations alone. Nevertheless, there is a great need to compare the observed changes in greenhouse effect to the changes in related parameters. Our study focuses on the annual cycle. The implication of this work will provide modeling study a surrogate of annual cycle of the greenhouse effect. For example, the model should be able to simulate the annual cycle before it can be used for global change study.

Relating the sea surface temperature, water vapor, and lapse rate to the seasonal cycle of the greenhouse effect have been addressed before by using spacebased observations in conjunction with the reanalysis product (Webb et al., 1993; Bony and Duvel, 1994). Results indicate that the lapse rate plays an important role in midlatitude regions. However, previous studies did not address the following problems: (1) Is there any zonal asymmetry? (2) Is water vapor in the upper troposphere important? (3) Previous study only used one year of data set in 1989, which may cause high uncertainties due to the interannual variations. Therefore, the purpose of our study is to address the above problems with longer data set.

2. DATA

In this study, we use coincident satellite observations from January 1985 to December 1989. Data are monthly averages and girded on 1°x1° grids. We focus on the oceanic areas.

* *Corresponding author address:* Dr. Hua Hu, Jet Propulsion Laboratory, M/S 300-323, 4800 Oak Grove Drive, Pasadena, CA91109, e-mail:
hxh@pacific.jpl.nasa.gov.

We use global sea surface temperature (SST) data set from NCAR. This data set combines satellite observations from the Advanced Very High Resolution Radiometer (AVHRR) with in situ measurements (Reynolds and Smith, 1995).

Global Outgoing Longwave Radiation (OLR) at the top of the atmosphere was measured by scanner instruments during the NASA Earth Radiation Budget Experiment (ERBE) (Barkstrom, 1984). The scanner instrument observed both clear-sky and all-sky OLR, however, we only use the clear-sky data in our study to separate the cloud-induced variability in the greenhouse effect. This data set is available from the NASA Langley EOS DAAC.

The greenhouse effect was calculated from the difference between the longwave emission from the

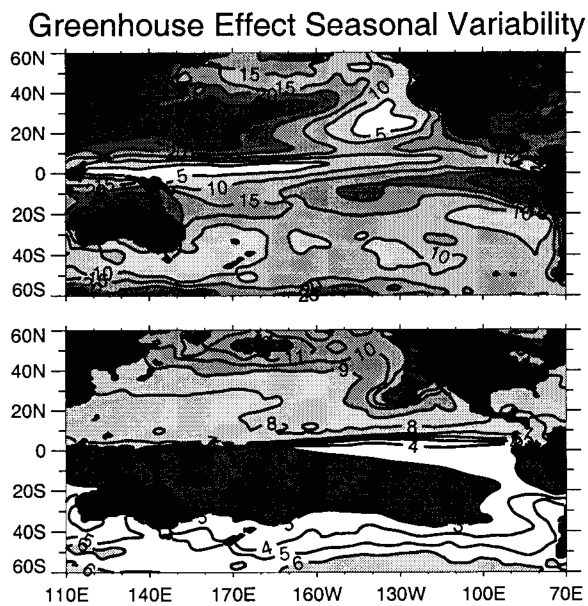

Figure 1. The top panel is the amplitude (scale factor is 1000^{-1}) of the annual cycle of the normalized clear-sky greenhouse effect. The contour interval is 5. The lower panel is the phase of the annual cycle, namely the month of maximum. Four seasons, Spring, Summer, Fall and Winter, are denoted by four shadings, from white to dark colors. Contour interval is 1 month. Areas with black color are over lands or with no data..

Earth's surface and the OLR at the top of the atmosphere. The normalized greenhouse effect is obtained by dividing the greenhouse effect by the longwave emission from the Earth's surface (Hu and Liu, 1998).

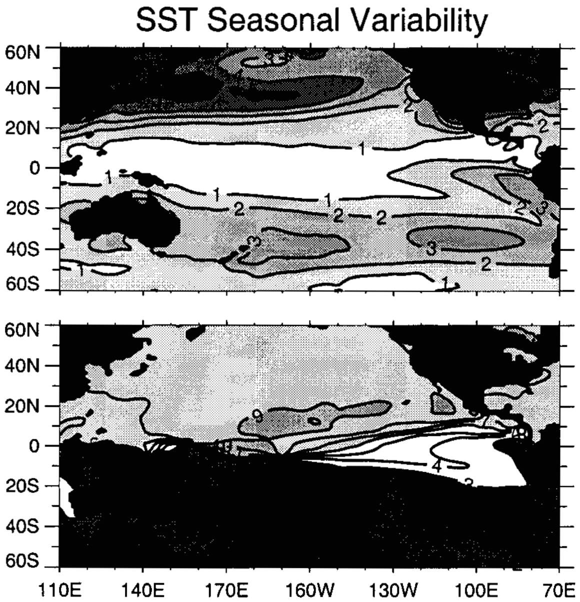

Figure 2. Same as the Figure 1, but for the annual cycle of the sea surface temperature. The contour interval for the top panel is 1 ^{o}C.

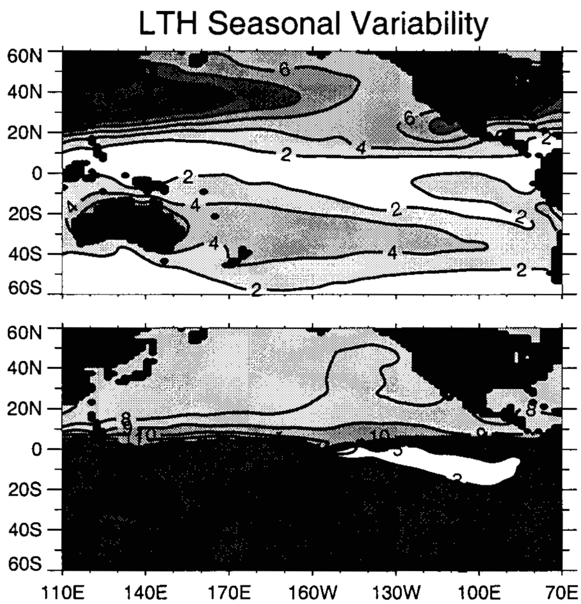

Figure 3. Same as the Figure 1, but for the annual cycle of the lower tropospheric humidity (LTH). The contour interval for the top panel is 2 cm with a scale factor of 10^{-1}.

We use the TOVS (TIROS Operational Vertical Sounder) water vapor data set distributed by the NASA Goddard DAAC center. Observations obtained from NOAA-9 and NOAA-10 satellites are used in this study. The original data set contains integrated water vapor (W) above five levels: surface, 850mb, 700mb, 500mb, and 300mb. In our study, we derived the lower tropospheric humidity (LTH) by subtracting W (700mb) from W (surface), and the upper tropospheric humidity (UTH) by subtracting W(300mb) from W(500mb). Thus, the LTH represents the mean humidity in the layer between surface and 700mb, and UTH represents the mean humidity in the layer between 500mb and 300mb.

Additionally, we use the reanalysis products from the National Center for Environment Prediction (NCEP) to calculate the temperature lapse rate in the troposphere. We obtain the mean mass-weighted lapse rate (Bony and Duvel, 1994), to represent the rough shape of the atmospheric temperature profile.

3. GEOGRAPHICAL DISTRIBUTION OF ANNUAL CYCLE

To extract the seasonal cycle, we performed a least-squares fit of an annual harmonic to the time series at each grid point for the normalized clear-sky greenhouse effect, SST, LTH, UTH, and lapse rate. The phase of the annual cycle is defined as the month of maximum value. Since five years of data were analyzed, the statistical uncertainties caused by interannual variability are low. Near the equator, the variation may be largely semi-annual, and at high latitudes, data may be contaminated by ice. We focus on the Pacific since the amplitude and phase in this area is already intriguing, as shown in Figures 1-5.

The greenhouse effect has larger seasonal variations in longitudes from 110^{o}E to 160^{0}W and latitudes between 10^{o}N to 45^{o}N, which are due to storm track variations and large seasonal variations in UTH. Also, larger seasonal variations are found in the eastern equatorial Pacific (cold tongue). Smaller seasonal variations are found over the western Pacific warm pool and subtropical high-pressure regions. For the phase, in the Tropics, the greenhouse effect reaches high in summertime, except in the cold tongue area in April and in the Subtropical High in later Fall/Winter. In mid and high latitudes, the greenhouse effect have maximum in wintertime. The relative importance of SST, LTH, UTH, and lapse rate to the annual cycle of the greenhouse effect at different locations are clearly demonstrated in Figures 1-5.

4. ZONAL DISTRIBUTION OF ANNUAL CYCLE

The overall seasonal cycle of the clear-sky greenhouse effect is better demonstrated in Figure 6. This figure shows the phase of the first harmonic of the zonally averaged seasonal variation for the clear-sky greenhouse effect, and the potential influencing factors. Again, near the equator, the variation may be largely semi-annual. High water vapor in lower troposphere and upper troposphere is found in summer. High SST follows one or two months behind since the atmosphere heats up faster than the ocean. Since water vapor is the major greenhouse gas, one would expect greenhouse effect follows water vapor. It is true at low latitudes but starting at around 30° polarward, the maximum greenhouse effect lags further behind, and the lag reaches almost four months at 50°. The phase change of atmospheric temperature lapse rate at 30° polarward may give a clue to the phase change of greenhouse warming, and is discussed in the next section.

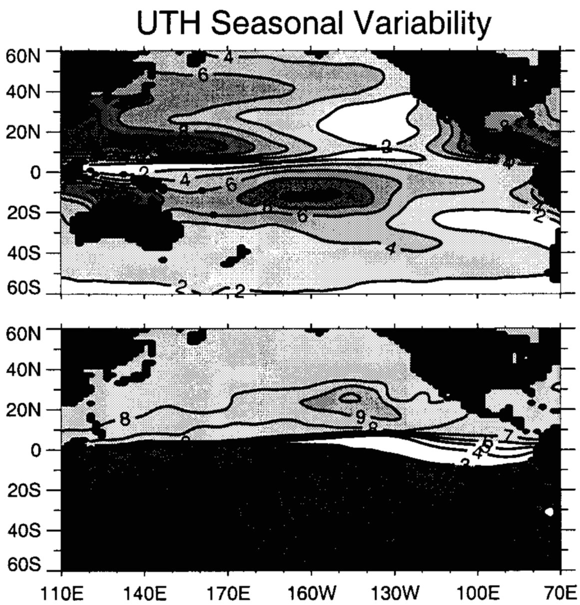

Figure 4. Same as the Figure 1, but for the annual cycle of the upper tropospheric humidity (UH). The contour interval for the top panel is 2 cm with a scale factor of 10^{-2}.

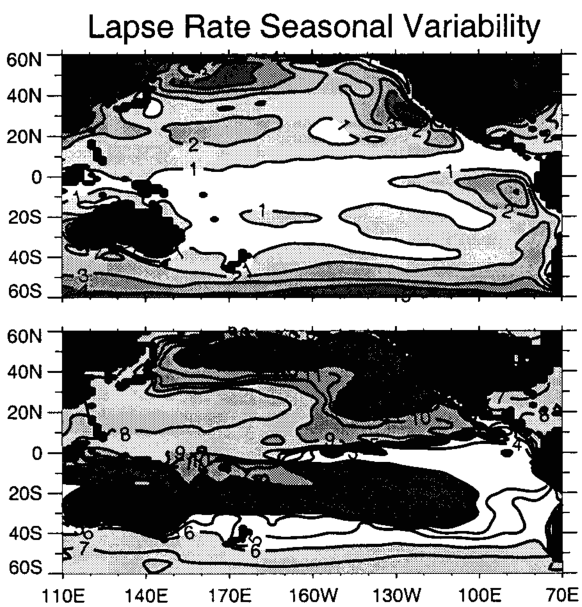

Figure 5. Same as the Figure 1, but for the annual cycle of the temperature lapse rate. The contour interval for the top panel is 1 K/km with a scale factor of 10^{-1}.

5. DISCUSSION

In order to understand the annual cycle in mid and high latitudes, we attempt to assess the relative importance of UTH and lapse rate since these two may be the most important factors. We computer the mean clear-sky greenhouse effect in given intervals of SST. In Figure 7 and 8, for a given UTH or lapse rate, the clear-sky greenhouse effect is larger for larger SST.

For a fixed interval of SST (that also implies approximate constant of LTH), the greenhouse effect decreases quickly with the UTH at low SST. Considering that increased UTH should lead increased clear-sky

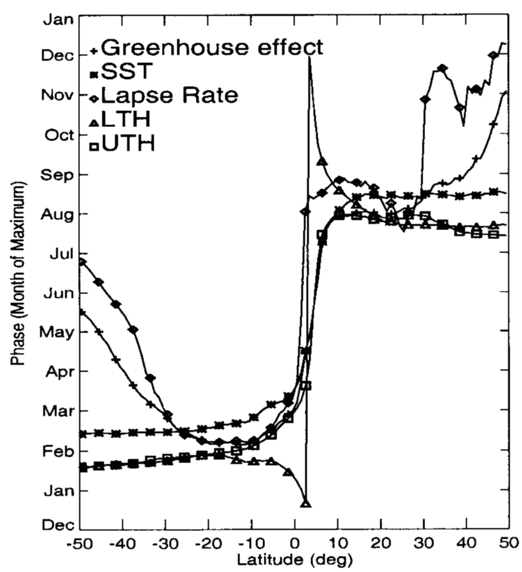

Figure 6. Phase of the first harmonic of the zonally averaged seasonal variation of the normalized clear-sky greenhouse effect, sea surface temperature, lower tropospheric humidity, upper tropospheric humidity, and the temperature lapse rate. The phase is the month of maximum. Zonally averaged over the oceanic areas.

greenhouse effect, a strong compensating effect must exist to explain the observed decrease in greenhouse effect. As shown in Figure 8, at low SST, the greenhouse effect increases quickly with the lapse rate. Although there is a tendency that higher UTH will result in higher clear-sky greenhouse effect, however, at the same time the upper tropospheric temperature will increase in order to hold more water vapor, thus the atmospheric emission will increase and the net greenhouse effect will decrease. Therefore, in mid and high latitudes, the annual cycle of greenhouse effect is mainly controlled by the lapse rate.

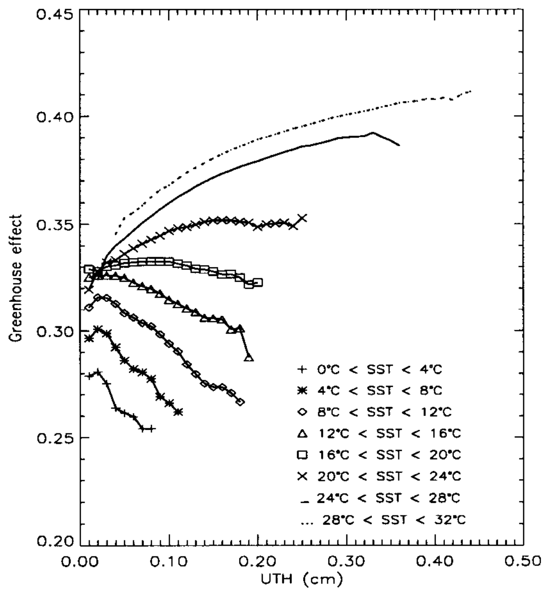

Figure 7. Mean relations between the upper tropospheric humidity and the clear-sky greenhouse effect in regular intervals of sea surface temperature.

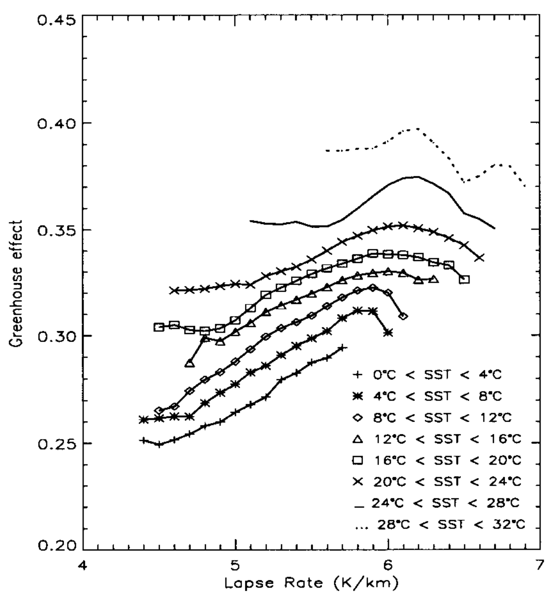

Figure 8. Same as the Figure 7, but for the temperature lapse rate and the clear-sky greenhouse effect.

At high SST, the clear-sky greenhouse effect increases quickly with the UTH and is less sensitive to lapse rate. This is because in Tropics, the lapse rate is close to moist adiabatic value, thus the UTH has a more important role than the lapse rate in influencing the annual cycle of the clear-sky greenhouse effect.

6. SUMMARY

Over ocean, in middle and high latitudes, the seasonal variation of the temperature lapse rate in the troposphere leads to large seasonal phase lags between greenhouse effect and lower and upper tropospheric humidity. By contracts, the seasonal variation of the clear-sky greenhouse effect over tropical ocean is mainly driven by sea surface temperature and tropospheric humidity. Our study also demonstrate that there islarge zonal asymmetry existing in the annual cycle of the greenhouse effect and its potential influencing factors.

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